DOE/NASA/2674-79/8
NASA TM-79305

EFFECT OF VELOCITY OVERSHOOT ON THE PERFORMANCE OF MAGNETOHYDRODYNAMIC SUBSONIC DIFFUSERS

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Work performed for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Magnetohydrodynamics Division

(NASA-TM-79305) EFFECT OF VELOCITY OVERSHOOT ON THE PERFORMANCE OF MAGNETOHYDRODYNAMIC SUBSONIC DIFFUSERS (NASA) 10 p HC A02/MF A01 CSCL 20I
N80-14922
Unclas
G3/75 46445

Prepared for
Eighteenth Aerospace Sciences Meeting
sponsored by the American Institute of Aeronautics and Astronautics
Pasadena, California, January 14-16, 1980

NOTICE

DOE/NASA/2064-79/8
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Energy Technology
Magnetohydrodynamics Division
Washington, D.C. 20545
Under Interagency Agreement EF-77-A-01-2674

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Abstract

The effect of velocity overshoot, a velocity distribution encountered in magnetohydrodynamic channels with peak velocity near the wall instead of at the center, on the performance of two-dimensional subsonic diffusers was investigated. For the simplified conditions analyzed in this paper it was found that the ratio of peak-to-centerline velocity increases along the diffuser for a diffuser half angle greater than some critical value. It was also found that irrespective of the accompanying inlet temperature distribution the wall shear stress and the wall heat flux is substantially larger when the inlet velocity profile has an overshoot than that for a fully developed turbulent inlet velocity profile.

I. Introduction

In ordinary channel flow the fluid is acted upon by a pressure force which is essentially constant across the channel and a viscous force which is zero at the center and maximum at the walls. Governed by these forces the velocity profile approaches a shape with maximum at the center (parabolic for laminar flows and flatter profiles for turbulent flows). In magnetohydrodynamic (MHD) power generator flows, the flow is also acted upon by a $\underline{j}\times\underline{B}$ Lorentz force. This is a retarding force when power is being extracted from the channel. Along the electrode wall, the $\underline{j}\times\underline{B}$ force is the same as in the free stream due to the requirement of current conservation. However, along the insulating wall the rapid decrease in electrical conductivity due to the large temperature differential between the free stream and the wall results in a similar decrease in the $\underline{j}\times\underline{B}$ force. As a result, the flow is slowed down more rapidly in the free stream than in the insulator wall boundary layer, which, depending upon flow conditions and the magnitude of the $\underline{j}\times\underline{B}$ force, can cause the maximum velocity of the flow profile to shift from the centerline into the boundary layer. This occurrence of a velocity maximum near the wall is termed velocity overshoot. These velocity overshoots have been theoretically predicted (references 1 and 2) and experimentally observed (ref. 3).

In the MHD power train a diffuser is attached to the exit of the generator channel. This paper theoretically investigates the effect of the velocity overshoot on the performance of the subsonic diffuser. The study is divided into two parts. In part one, given in section II, the evolution of an overshoot velocity distribution is studied in a plane two-dimensional diffuser as a function of diffuser divergence angle. In part two, given in section III, the diffuser performance for velocity overshoot is compared to that for fully developed inlet velocity profile.

The computations were carried out using a newly developed method (ref. 4) to calculate two-dimensional momentum and energy transport for a viscous compressible flow. In this method the flow in the duct is partitioned into finite streams. The difference equations are then obtained by applying momentum and energy conservation principles directly to the individual streams. For simplicity in our initial analysis, all calculations have been carried out for air assuming a perfect gas with constant specific heat and an inlet static pressure of 1 atm.

II. Evolution of Velocity Overshoot as a Function of Diffuser Angle

In initial calculations utilizing a two-dimensional diffuser with a two degree half angle, an unexpected phenomena was observed. It was observed that the ratio of the peak velocity (velocity of the overshoot) to the centerline velocity increased with distance down the diffuser. This was unexpected since it was initially thought that viscous forces would tend to dampen the effect of the velocity overshoot.

In order to more closely examine the above phenomena a study was carried out to investigate the effect of friction on the damping of the overshoot at various diffuser half angles. Furthermore in order to minimize any influence that heat transfer might have upon the phenomena, the calculations were carried out with the inlet centerline and wall temperatures set equal to 2000K. The inlet Mach number based on the centerline velocity was set equal to .8 which is in the neighborhood of the expected exiting Mach number from a subsonic MHD power generator. The inlet velocity profile (see figure 1) was choosen as a convenient mathematical simulation of the velocity overshoot profile calculated in reference 1.

Figure 1 shows the evolution of the overshoot velocity distribution in a two-dimensional diffuser with a two degree half angle. In this and the other figures the following nomenclature is used:

- x, distance along the diffuser centerline,
- z, distance from the diffuser wall,
- H_0, diffuser height at the inlet,
- H, diffuser height at x.

As previously discussed, figure 1 shows that while the velocity as a whole decreased down the diffuser, that the ratio of the peak-to-centerline velocity does not decrease. In fact this ratio increases with distance along the diffuser. The suspected reason for this somewhat unexpected behavior is that while viscous forces tend to smear out the peak, the rising pressure in the decelerating flow accentuates the velocity differences normal to the flow, i.e. a fast moving stream has to slow down less than a slow moving stream to overcome the same pressure rise.

In order to check the validity of the above observation several cases were run with different diffuser divergence angles since if the above explanation of the phenomena is correct then at a small enough divergence angle the friction forces must eventually dominate and result in a damping of the overshoot. Figure 2 shows the evolution of the overshoot inlet velocity distribution for zero divergence angle, i.e. for flow through a constant area duct. We note that for this case the ratio of peak-to-centerline velocity decreases with distance down the duct. In this case pressure falls along the duct and the decreasing pressure helps the viscous forces to smear out the velocity overshoot. Figure 3 shows the variation of the peak-to-centerline velocity ratio along the diffuser for various divergence angles. In all cases the flow conditions at the inlet are identical. The leveling off of the growth in peak-to-centerline velocity ratio for two and three degree half angles is due to the leveling off of the pressure rise as the flow travels down the diffuser.

III. Comparison of Diffuser Performance for Velocity Overshoot and Fully Developed Inlet Profiles

In actuality both the velocity and temperature profiles are specified by the MHD generator exit conditions. The degree of velocity overshoot, if any, and the effect upon the temperature profile are strongly dependent upon the operating characterisitics of the MHD generator. Therefore, to investigate the general character of the effects associated with velocity overshoot, three difference representative combinations of inlet velocity and temperature profiles were examined. To provide a common basis on which to compare the three different cases, the representative inlet conditions were selected for case 1 and conditions for the two other cases (cases 2 and 3) were selected to match the mass flow rate and stagnation enthalpy of case 1. In all cases the inlet static pressure and wall temperature were 1 atm and 1500K respectively.

Case 1: Fully developed Velocity - Fully Developed Temperature - In this case the velocity u and temperature T at the inlet are calculated from the formula,

$$\frac{u}{u_c} = \frac{T - T_w}{T_c - T_w} = \frac{z}{z_c}^{1/7}$$

where subscription c amd w refer to the wall and centerline conditions respectively.

Typical numerical values for the exit of a MHD generator were selected for the centerline velocity and temperature of 717.5 M/S and 2200K respectively. These correspond to a Mach number of 0.8.

Case 2: Overshoot Velocity - Fully Developed Temperature - Lacking specific data as to the explicit form of the overshoot velocity profile, a mathematically convenient approximation of the profile given in reference 1 was used. In this approximation the variation of velocity from the wall to the peak is taken as $z^{1/7}$ and the peak velocity is fifty percent greater than the centerline velocity. Of even greater uncertainty is the associated temperature profile. It is therefore the choice of the profile that separates cases two and three. In this case the limit of a fully developed temperature profile was assumed as in the previous case.

$$\frac{T - T_w}{T_c - T_w} = \frac{z}{z_c}^{1/7}$$

The inlet centerline velocity and temperature were 565.7 M/S and 2008.7K respectively to match the mass flow rate and stagnation enthalpy of case 1.

Case 3: Overshoot Velocity - Overshoot Temperature - In this case the velocity profile is identical to that of case two but a limiting case in which the temperature profile is identical to the velocity is considered so that the temperature is given by:

$$\frac{T - T_w}{T_c - T_w} = \frac{u}{u_c}$$

and the equivalent inlet centerline velocity and temperature of 566.7 M/S and 1892K respectively.

Calculated Results

The inlet velocity and temperature profiles for the above three cases are presented in figures 4a and 5a.

The diffuser flow for the three specified cases was two degree half angle, one meter in height at the inlet, and ten meters long. Results of the calculations are shown in figures 4 through 8. Figure 4b shows the velocity profiles at the diffuser exit for the three different cases. We note, that for the conditions considered here, that irrespective of the accompanying temperature profile the velocity overshoot persists up to the end of the diffuser. Figure

5b shows the temperature profiles at the diffuser exit. We note that the temperature overshoot for the OVERSHOOT VELOCITY--OVERSHOOT TEMPERATURE case has substantially disappeared. The exit temperature profile for the OVERSHOOT VELOCITY--FULLY DEVELOPED TEMPERATURE case shows a sudden change in the slope near the wall. The point of sudden change corresponds roughly to the point of peak velocity and is possibly due to the compression work associated with slowing down this velocity peak.

Figure 6 shows the pressure rise along the diffuser for the three cases. The insignificant difference between the different cases indicates that the pressure rise is almost solely due to the area change and hence the pressure recovery should be nearly identical for the three cases. However, from figure 7, which shows the shear stress at the wall, we note that irrespective of the accompanying temperature profile the velocity overshoot case has two and a half to four times the wall shear stress compared to the fully developed velocity profile case. Thus, as noted in references 1 and 2, the velocity overshoot condition should be less susceptible to separation than profiles of the fully developed form. This indicates that the electrode wall which does not possess velocity overshoot will probably separate before the insulator wall unless it is designed with smaller divergence angle.

Figure 8 shows heat flux to the wall for the three cases. The substantially larger heat flux to the wall in the case of OVERSHOOT VELOCITY--OVERSHOOT TEMPERATURE as compared to the FULLY DEVELOPED VELOCITY--FULLY DEVELOPED TEMPERATURE case is partly due to the higher temperature (temperature overshoot peak) in the vicinity of the wall and partly due to enhanced convection caused by the higher velocity (velocity overshoot peak) near the wall. In the case of OVERSHOOT VELOCITY--FULLY DEVELOPED TEMPERATURE the increase in heat flux is primarily due to the increased convection. As we proceed down the diffuser the temperature overshoot, as seen from figure 5, gradually disappears and the heat flux to the wall for the two cases OVERSHOOT VELOCITY--OVERSHOOT TEMPERATURE and OVERSHOOT VELOCITY--FULLY DEVELOPED TEMPERATURE should approach each other. This is illustrated in the results shown in figure 8. The large heat flux to the wall exhibited by the velocity overshoot cases indicates that the velocity profile exiting the MHD generator will also have a serious effect upon the overall heat transfer design of the diffuser.

IV. Concluding Remarks

In this preliminary study of the effects upon diffuser performance resulting from the overshoot velocity profiles characteristic of the flow along the insulator walls at the exit of a MHD generator, a number of simplifying assumptions were made. A two-dimensional calculation was used, air was assumed to be the working fluid and in addition it was assumed to be a perfect gas, and a mathematically convenient representation of the velocity overshoot profile calculated in reference 1 was assumed. In actuality the working fluid will be combustion products and the degree of velocity overshoot, if any, will be determined by the performance characteristics of the MHD generator. Therefore the conclusions reached in this preliminary study are restricted by the limitations of the input conditions. A comparison between velocity overshoot and fully-developed profiles indicates the velocity overshoot condition to have significantly greater wall shear stress and hence should be less susceptible to flow separation than the fully-developed profile. The heat flux associated with the overshoot conditions is however higher, and hence will have a serious effect upon the overall heat transfer design of the diffuser. An unsuspected result of this investigation was the amplification of the velocity overshoot for diffuser divergence angles greater than some critical value due to the dominance of pressure effects relative to the damping effects of viscosity. The effects of flow separation, half angle divergences, and total pressure recovery are presently being studied for the more realistic condition of a combustion gas working fluid and for a range of velocity overshoot magnitudes and profiles.

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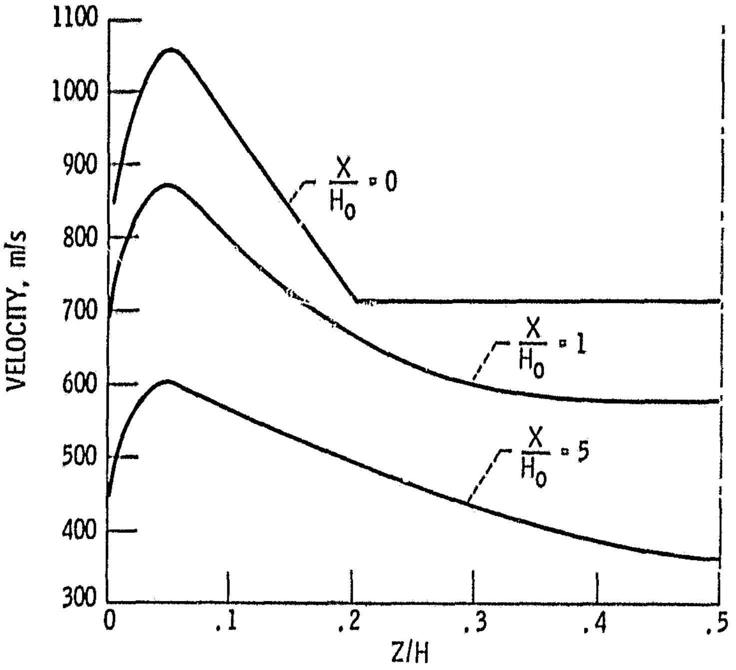


Figure 1. - Velocity profile evolution for 2° diffuser half angle.

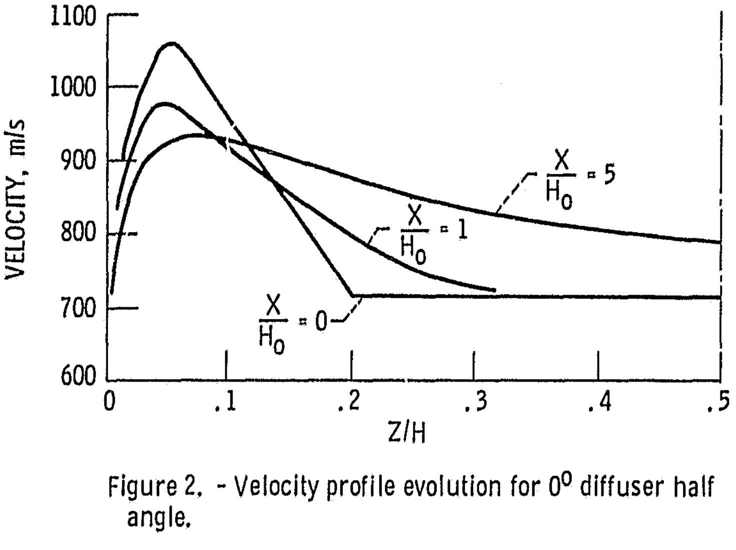


Figure 2. - Velocity profile evolution for 0° diffuser half angle.

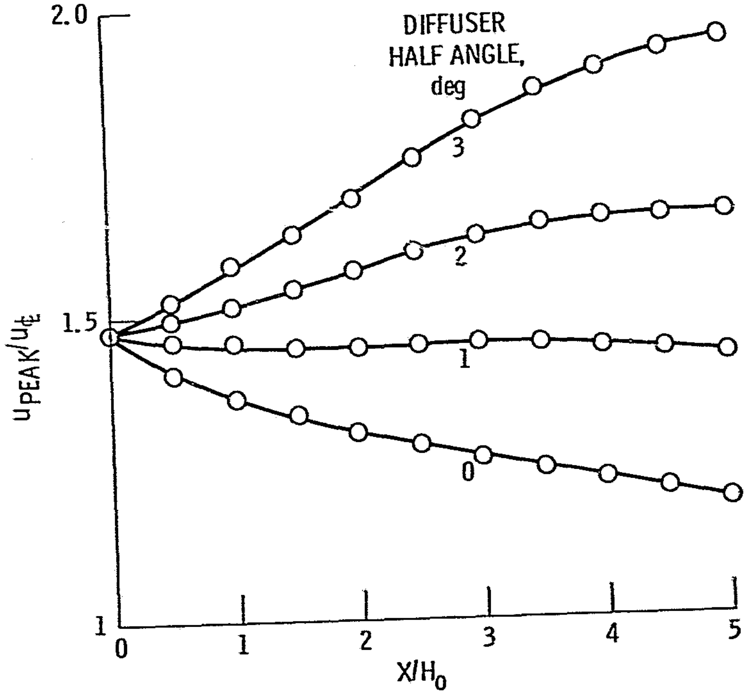
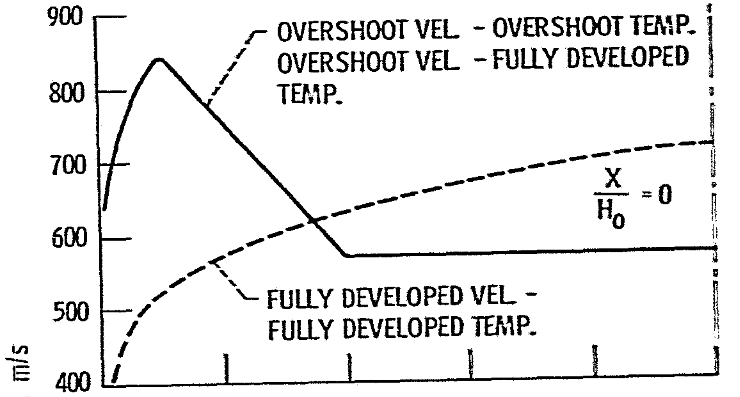
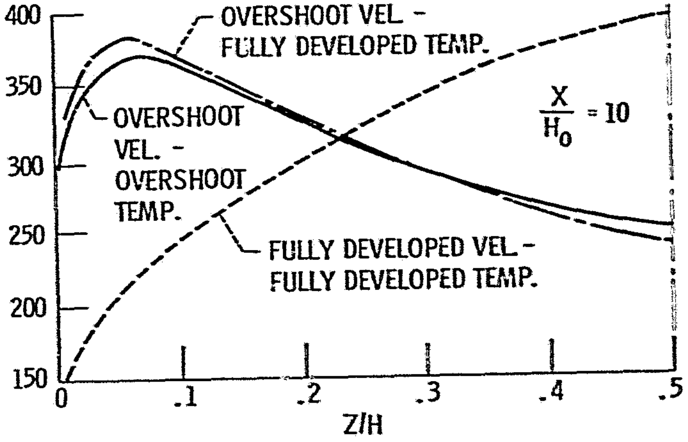


Figure 3. - Ratio of peak to centerline velocity as function of distance down duct.

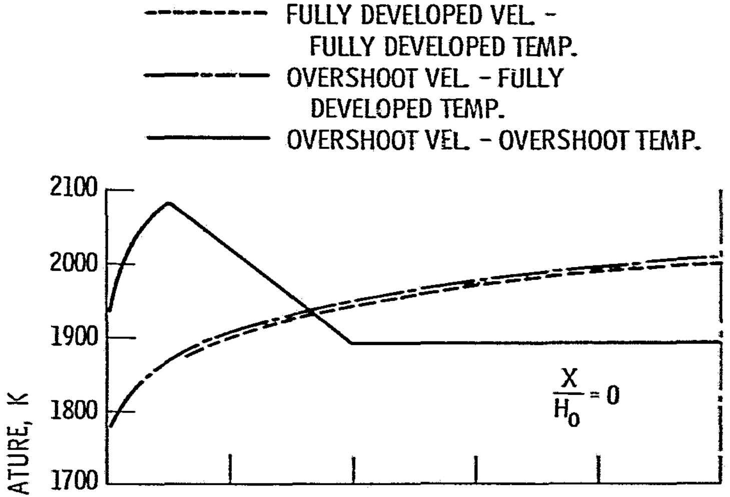


(a) AT DIFFUSER INLET.

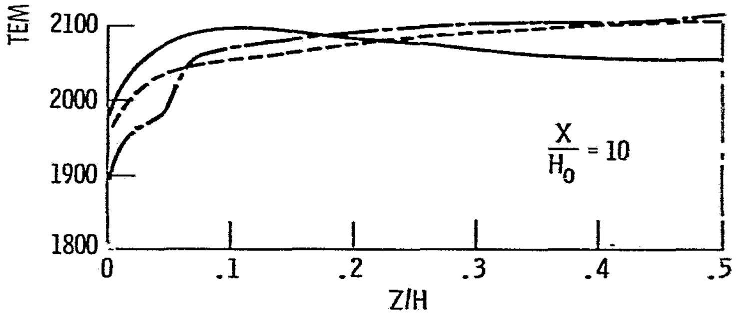


(b) AT 10 METERS.

Figure 4. - Velocity profiles.



(a) AT DIFFUSER INLET.



(b) AT 10 METERS.

Figure 5. - Temperature profiles.

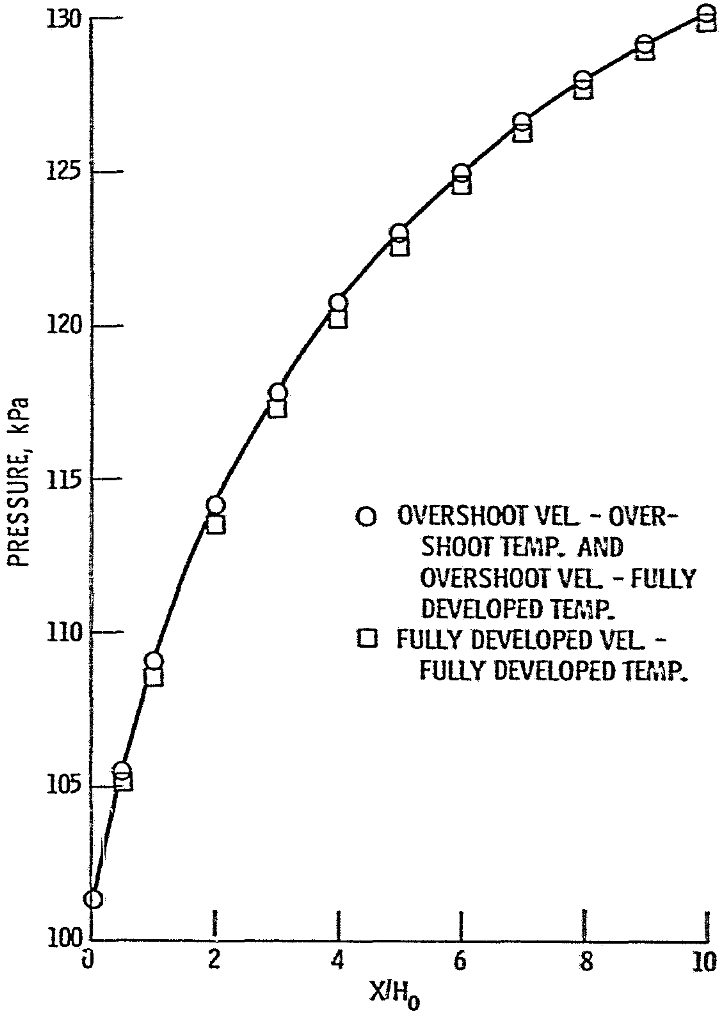


Figure 6. - Axial pressure distribution.

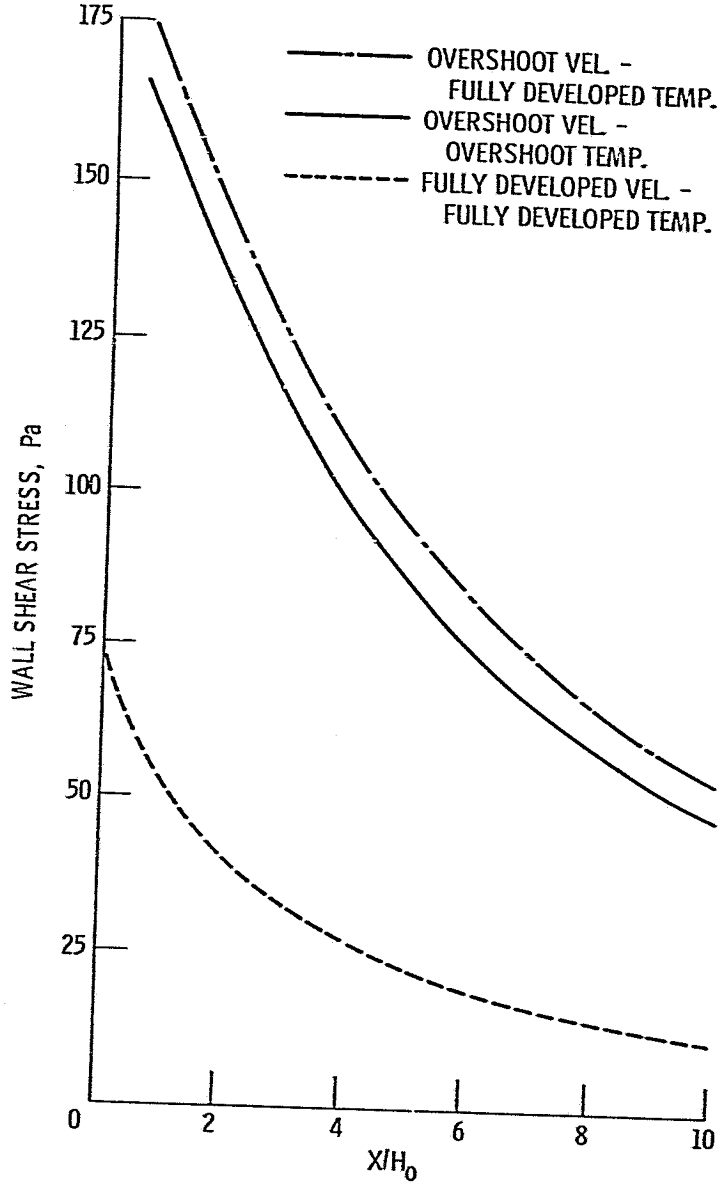


Figure 7. - Axial wall shear stress distribution.

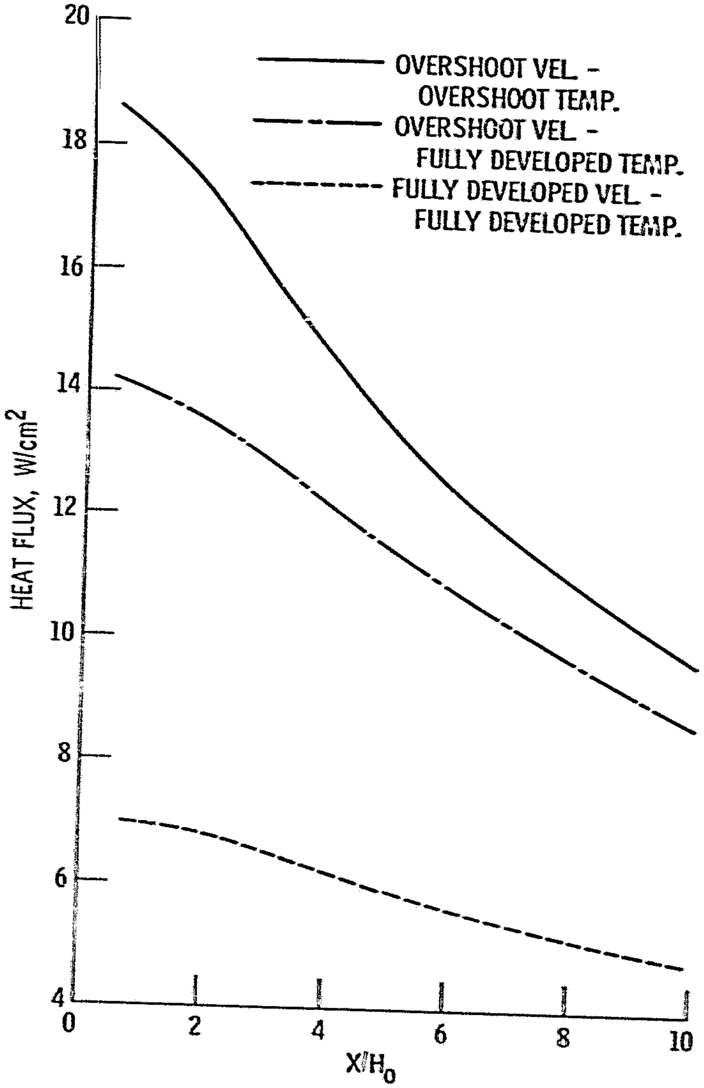


Figure 8. - Axial heat flux distribution.

1. Report No NASA TM-79305	2. Government Accession No	3. Recipient's Catalog No
4. Title and Subtitle EFFECT OF VELOCITY OVERSHOOT ON THE PERFORMANCE OF MAGNETOHYDRODYNAMIC SUBSONIC DIFFUSERS		5. Report Date 6. Performing Organization Code
7. Author(s) Mahesh S. Greywall, Wichita State University, Wichita, Kansas, and J. Marlin Smith, Lewis Research Center		8. Performing Organization Report No E-257
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. Work Unit No 11. Contract or Grant No
12. Sponsoring Agency Name and Address U.S. Department of Energy Magnetohydrodynamics Division Washington, D.C. 20545		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/2674-79/8

15. Supplementary Notes Prepared under Interagency Agreement EF-77-A-01-2674. Prepared for the Eighteenth Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics, Pasadena, California, January 14-16, 1980.

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17. Key Words (Suggested by Author(s)) Diffuser Magnetohydrodynamics	18. Distribution Statement Unclassified - unlimited STAR Category 75 DOE Category UC 90G

19. Security Classif (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161